

Exclusive $D\bar{D}$ meson pair production in peripheral ultrarelativistic heavy ion collisions

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Abstract

The cross sections for exclusive D^+D^- and $D^0\bar{D}^0$ meson pair production in peripheral nucleus - nucleus collisions are calculated and several differential distributions are presented. The calculation of the elementary $\gamma\gamma \rightarrow D\bar{D}$ cross section is done within the heavy-quark approximation and in the Brodsky- Lapage formalism with distribution amplitudes describing recent CLEO data on leptonic D^+ decay. Realistic (Fourier transform of charge density) charge form factors of nuclei are used to generate photon flux factors. Absorption effects are discussed and quantified. The cross sections of a few nb are predicted for RHIC and of a few hundreds of nb for LHC with details depending on the approximation made in calculating elementary $\gamma\gamma \rightarrow D\bar{D}$ cross sections.

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I. INTRODUCTION

The main aim of the heavy ion program at ultrarelativistic collision energies is concentrated on the discovery and analysis of the quark-gluon plasma. High charges of the colliding ions give a possibility to study also peripheral processes when only a few particles are produced. In particular, large fluxes of photons associated with the huge charges of nuclei open an interesting possibility to study photon-photon collisions [1] which are difficult to study in e^+e^- and proton-proton collisions.

In our earlier works we have studied a production of $\mu^+\mu^-$ [2], $\rho^0\rho^0$ [3] and recently of $c\bar{c}$ and $b\bar{b}$ [4]. We have demonstrated how important is the inclusion of the realistic charge form factors responsible for generating photon flux factors. In our analysis charge form factors of nuclei are calculated as Fourier transform of the realistic charge densities as measured in electron scattering off nuclei.

Many years ago Brodsky and Lepage have suggested how to calculate large-angle production of light meson pairs ($\pi\pi$, $K\bar{K}$) in photon-photon collisions. In the meantime several further studies have been performed and some improvements have been suggested. Parallel those processes were searched for in several experimental studies.

Heavy quark meson pair production was studied theoretically only in Ref.[5] where formulas have been derived in the heavy quark approximation with Dirac delta-like distribution amplitudes. On the other hand both lattice QCD [6] and the CLEO collaboration [7] extracted the D-meson distribution amplitude which turned out to differ considerably from the delta-like distribution amplitude assumed in heavy quark approximation. In the present studies we will use also the more realistic distribution amplitudes.

Both LEP2 and Belle studies were not able to extract corresponding cross sections. The nuclear processes look potentially interesting in this respect due to the large charges of the colliding ions. In the present analysis we wish to calculate cross sections for exclusive production of D^+D^- meson pairs in $AA \rightarrow AAD\bar{D}$ reactions at RHIC (Au+Au, $W_{NN} = 200$ GeV) and LHC (Pb+Pb, $W_{NN} = 5.5$ TeV). Whether the experimental analysis is possible requires experimental feasibility studies.

In Fig.1 we show the basic QED mechanism of the exclusive production of $D\bar{D}$ pairs in the peripheral heavy-ion collisions. We consider both D^+D^- and $D^0\bar{D}^0$ production.

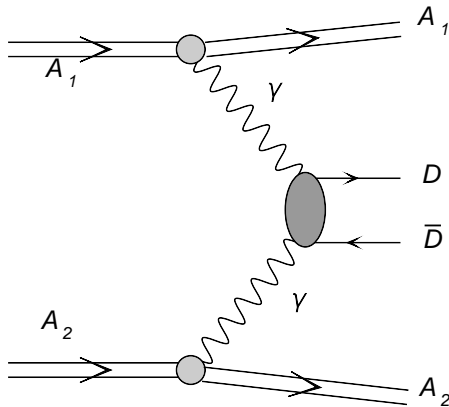


FIG. 1: The diagram for the exclusive $D\bar{D}$ meson production.

In the next section we concentrate on the calculation of the cross section for the $\gamma\gamma \rightarrow D\bar{D}$ reaction which, as discussed in section II, is used in the equivalent photon approximation in

the impact parameter space (b-space EPA). The nuclear cross sections are presented in the result section. Conclusions and summary close our paper.

II. HEAVY CHARMED MESON PAIR PRODUCTION IN PHOTON- PHOTON COLLISIONS

In this section we discuss how to calculate the elementary cross section for the $\gamma\gamma \rightarrow D\bar{D}$ reaction. For the rather heavy mesons a pQCD approach seems the best method to calculate the cross section. In the leading order of α_s , 20 Feynman diagrams are involved as shown in Fig.2. The diagrams can be classified into three groups. Six diagrams of first part in Fig.2 represent the heavier- quark pair production by two- photon collisions followed by one virtual gluon emission to allow the produced heavier quarks to hadronize into heavy mesons. The second part of the figures shows diagrams obtained by exchanging heavier quark lines with lighter antiquark lines. The last part consists of eight diagrams where one photon produces a pair of heavier quarks and the other photon produces a pair of lighter quarks.

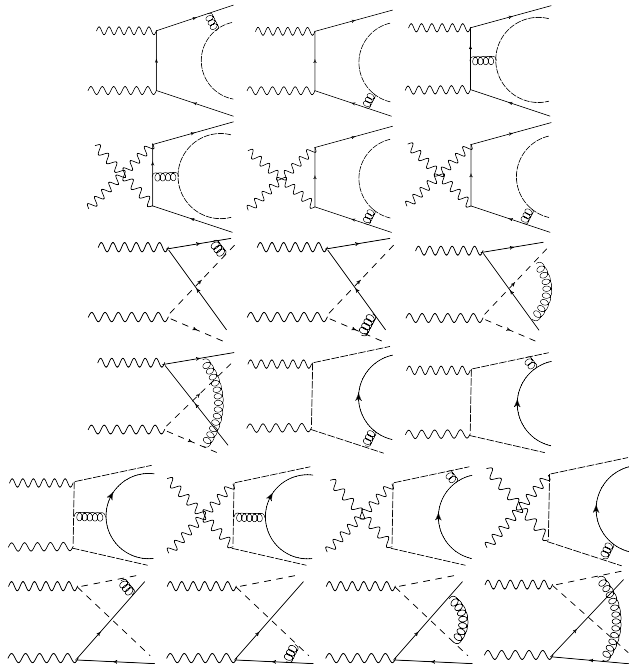


FIG. 2: Heavy meson pair production in photon-photon collision. The wiggly (curly) line is for a photon (gluon), while the solid (dotted) one is for the heavier (lighter) (anti)quark.

In Ref.[5] the distribution amplitudes of the form:

$$\Phi_M(x, Q^2) = f(x, Q^2) \frac{1+V}{2} \gamma_5, \Phi_{\bar{M}}(x, Q^2) = f^*(x, Q^2) \frac{1-V}{2} \gamma_5 \quad (2.1)$$

have been assumed with the heavy-quark approximation

$$f(x, Q^2) = f^*(x, Q^2) = \delta(x - \Lambda/M), \quad (2.2)$$

where $\Lambda = M - m_Q$.

The resulting pseudoscalar-pseudoscalar (PP) production amplitude $M_{PP}^{\gamma\gamma}(\lambda, \lambda')$ can be written as [5]

$$M_{PP}^{\gamma\gamma}(\lambda, \lambda') = 2 \frac{F^{\gamma\gamma}}{(1-z^2)^2} (1+z^2) \left[e_Q^2 F_{PP}(\lambda, \lambda') + e_q^2 F'_{PP}(\lambda, \lambda') \right] - 2e_Q e_q G_{PP}(\lambda, \lambda') \\ - (1-z^2) \left[\frac{1-x}{x} e_Q^2 H_{PP}(\lambda, \lambda') + \frac{x}{1-x} e_q^2 H'_{PP}(\lambda, \lambda') \right], \quad (2.3)$$

where

$$F^{\gamma\gamma} = \frac{16\pi^2 \alpha_e \alpha_s C_F}{\hat{s} x^2 (1-x)^2} \left[\frac{f_M}{M} \right], \quad (2.4)$$

$$F_{PP}(\lambda, \lambda') = \left[(1-x)[2-x(\hat{s}+2)] + \frac{\hat{s}}{2} \sigma_{\lambda, -\lambda'} \right] (\beta^2 - z^2), \quad (2.5)$$

$$F'_{PP}(\lambda, \lambda') = \left[x - [2 - (1-x)(\hat{s}+2)] \frac{\hat{s}}{2} \sigma_{\lambda, -\lambda'} \right] (\beta^2 - z^2), \quad (2.6)$$

$$G_{PP}(\lambda, \lambda') = \left[\frac{\hat{s}}{2} [1+z^2 + (1-z^2)\sigma_{\lambda, -\lambda'}] - 2x(1-x(2+\hat{s})) \right] \\ (\beta^2 - z^2) - [\hat{s}(1-z^2) - 2(3-z^2)\sigma_{\lambda, -\lambda'}], \quad (2.7)$$

$$H_{PP}(\lambda, \lambda') = [2-x(\hat{s}+2)] \left[(1-x)\beta^2 - z^2 \right] + z^2 \sigma_{\lambda, -\lambda'} + x(\hat{s}+2)\sigma_{\lambda, -\lambda'}, \quad (2.8)$$

$$H'_{PP}(\lambda, \lambda') = [2 - (1-x)(\hat{s}+2)] \left[x(\beta^2 - z^2) + z^2 \sigma_{\lambda, -\lambda'} \right] \\ + (1-x) + x(\hat{s}+2)\sigma_{\lambda, -\lambda'}. \quad (2.9)$$

In the formulas above: $\hat{s} = \frac{s}{M^2}$, $z = \beta \cos\theta$, and $\beta = \sqrt{1 - \frac{4}{\hat{s}}}$.

The θ is the scattering angle between the photon and a heavy meson, the color factor $C_F = \frac{4}{3}$.

In the $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ reaction usually cuts on $z = \cos\theta$, where θ is the angle in the photon-photon center of mass frame, are imposed. This type of cuts is rather difficult to realize in the $AA \rightarrow AAD\bar{D}$ reactions where kinematics is usually incomplete. However, very often transverse momenta of charged pions can be easily measured with modern detectors. Therefore in the following we impose cuts on transverse momenta of both charmed mesons. In order not to lose too much of the signal we require only $p_t > 1$ GeV.

In Fig.3 we show the energy dependence of the elementary $\gamma\gamma \rightarrow D^+D^-(D^0\bar{D}^0)$ cross sections calculated according to the formalism used in Ref. [5] with the cut on meson transverse momenta. The cross section for $D^0\bar{D}^0$ is larger than that for D^+D^- close to the threshold but falls faster with increasing $W_{\gamma\gamma}$.

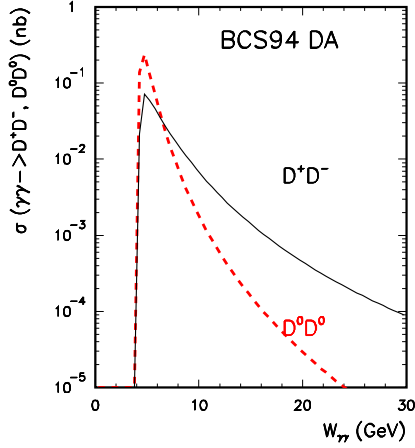


FIG. 3: The energy dependence of the $\gamma\gamma \rightarrow D^+D^-$ (black line) and $\gamma\gamma \rightarrow D^0\bar{D}^0$ (dashed, red online) in the heavy-quark approximation [5]. In this calculations we have imposed an extra cut on the D-meson transverse momenta $p_t > 1$ GeV.

Above we have used the heavy quark approximation, i.e. we have assumed that light quark/antiquark carries a fixed fraction of the final meson momentum, $x = \frac{\Lambda}{M} = \frac{M-m_q}{M}$ and used hard process matrix elements with finite heavy quark masses. At present, it is known that the distribution amplitude is not of the Dirac delta type (see e.g. [10] and references therein).

Therefore in the following we use also the classical Brodsky-Lepage formalism [11] with distribution amplitudes taken from the recent studies [10]. In this approach the normalized to unity distribution amplitude is given as

$$\phi_D(x) = \frac{\sqrt{6}A_D y}{8\pi^{3/2}f_D} \sqrt{x(1-x)} \left[1 - \text{Erf}\left(\frac{b_D y}{\sqrt{x(1-x)}}\right) \right] \exp \left[-b_D^2 \frac{(xm_2^{*2} + (1-x)m_1^{*2} - y^2)}{x(1-x)} \right], \quad (2.10)$$

where $y = xm_2^* + (1-x)m_1^*$, $\text{Erf}(x) = \frac{2}{\pi} \int_0^x \exp(-t^2) dt$ and m_1^* and m_2^* are quark (constituent) masses. We take the parameters in Eq.(2.10) from [10]: $P_D \simeq 0.8$, $A_D = 116$ GeV, $b_D = 0.592$ GeV $^{-1}$, $f_D = 0.223$ GeV.

In the Brodsky-Lepage formalism the amplitude for the $\gamma\gamma \rightarrow D\bar{D}$ process can be written schematically as:

$$\mathcal{M}_{\gamma\gamma \rightarrow D\bar{D}} = \int \Phi^*(x, \mu^2) H_{\lambda_1 \lambda_2}(x, y, z) \Phi(y, \mu^2) dx dy. \quad (2.11)$$

Above $H_{\lambda_1 \lambda_2}(x, y, z)$ is the photon helicity dependent hard matrix element for $\gamma\gamma \rightarrow q\bar{Q}\bar{q}Q$ and Φ 's are Brodsky-Lepage distribution amplitudes. The distribution amplitude Φ here is related to the distribution amplitude in Eq.(2.10) as:

$$\Phi(x) = \frac{f_D}{2\sqrt{3}} \phi_D(x). \quad (2.12)$$

In Fig.4 we show elementary cross section as a function of the $\gamma\gamma$ subsystem energy for the Brodsky-Lepage formalism. As in the heavy-quark approximation an extra cut on the

D meson transverse momentum, $p_t > 1$ GeV, has been imposed. While the cross section for D^+D^- is similar in both approaches, the cross sections for $D^0\bar{D}^0$ differ considerably.

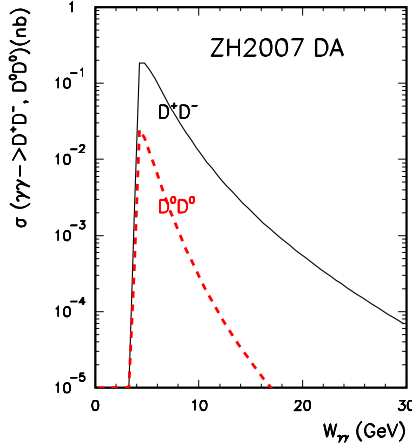


FIG. 4: The energy dependence of the $\gamma\gamma \rightarrow D^+D^-$ (black line) and $\gamma\gamma \rightarrow D^0\bar{D}^0$ (dashed, red online) in the Brodsky-Lepage formalism [11] with distribution amplitude from [10]. In this calculations we have imposed an extra cut on the D-meson transverse momenta ($p_t > 1$ GeV).

III. NUCLEAR COLLISIONS, EQUIVALENT PHOTON APPROXIMATION

To calculate the cross section of the nuclear process it is convenient to introduce a new kinematic variable: $x = \frac{\omega}{E_A}$, where ω is the energy of the photon and the energy of the nucleus $E_A = \gamma A m_{proton} = \gamma M_A$, where M_A is the mass of the nucleus and γ is the Lorentz factor.

The total cross section can be calculated by the convolution [2]:

$$\sigma(AA \rightarrow AAD\bar{D}; s_{AA}) = \int \hat{\sigma}(\gamma\gamma \rightarrow D\bar{D}; W_{\gamma\gamma} = \sqrt{x_1 x_2 s_{AA}}) dn_{\gamma\gamma}(x_1, x_2, \mathbf{b}). \quad (3.1)$$

The effective photon fluxes can be expressed through the electric fields generated by the nuclei:

$$\begin{aligned} dn_{\gamma\gamma}(x_1, x_2, \mathbf{b}) = & \frac{1}{\pi} d^2\mathbf{b}_1 |\mathbf{E}(x_1, \mathbf{b}_1)|^2 \frac{1}{\pi} d^2\mathbf{b}_2 |\mathbf{E}(x_2, \mathbf{b}_2)|^2 \\ & \times S_{abs}^2(\mathbf{b}) \delta^{(2)}(\mathbf{b} - \mathbf{b}_1 + \mathbf{b}_2) \frac{dx_1}{x_1} \frac{dx_2}{x_2}. \end{aligned} \quad (3.2)$$

The presence of the absorption factor $S_{abs}^2(\mathbf{b})$ assures that we consider only peripheral collisions, when the nuclei do not undergo nuclear breakup. In the first approximation this can be expressed as:

$$S_{abs}^2(\mathbf{b}) = \theta(\mathbf{b} - 2R_A) = \theta(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A). \quad (3.3)$$

Thus in the present case, we concentrate on processes with final nuclei in the ground state. The electric field strength can be expressed through the charge form factor of the nucleus:

$$\mathbf{E}(x, \mathbf{b}) = Z\sqrt{4\pi\alpha_{em}} \int \frac{d^2\mathbf{q}}{(2\pi^2)} e^{-i\mathbf{b}\mathbf{q}} \frac{\mathbf{q}}{\mathbf{q}^2 + x^2 M_A^2} F_{em}(\mathbf{q}^2 + x^2 M_A^2). \quad (3.4)$$

Next we can benefit from the following formal substitution:

$$\frac{1}{\pi} \int d^2\mathbf{b} |\mathbf{E}(x, \mathbf{b})|^2 = \int d^2\mathbf{b} N(\omega, \mathbf{b}) \equiv n(\omega) \quad (3.5)$$

by introducing effective photon fluxes which depend on energy of the quasireal photon ω and the distance from the nucleus in the plane perpendicular to the nucleus motion \vec{b} . Then, the luminosity function can be expressed in term of the photon flux factors attributed to each of the nuclei

$$dn_{\gamma\gamma}(\omega_1, \omega_2, \mathbf{b}) = \int \theta(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A) N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) d^2\mathbf{b}_1 d^2\mathbf{b}_2 \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2}. \quad (3.6)$$

The total cross section for the $AA \rightarrow AAD\bar{D}$ process can be factorized into the equivalent photons spectra ($n(\omega)$) and the $\gamma\gamma \rightarrow D\bar{D}$ subprocess cross section as (see e.g. [9]):

$$\begin{aligned} \sigma(AA \rightarrow AAD\bar{D}; s_{AA}) &= \int \hat{\sigma}(\gamma\gamma \rightarrow D\bar{D}; W_{\gamma\gamma}) \theta(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A) \\ &\times N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) d^2\mathbf{b}_1 d^2\mathbf{b}_2 \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2}, \end{aligned} \quad (3.7)$$

where $W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$ is energy in the $\gamma\gamma$ subsystem.

$$\sigma(AA \rightarrow AAD\bar{D}) = \int \hat{\sigma}(\gamma\gamma \rightarrow D\bar{D}; \sqrt{4\omega_1\omega_2}) n(\omega_1) n(\omega_2) \frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2}. \quad (3.8)$$

Additionally, we define $Y = \frac{1}{2}(y_D + y_{\bar{D}})$, rapidity of the outgoing meson system which is produced in the photon-photon collision. Performing the following transformations:

$$\omega_1 = \frac{W_{\gamma\gamma}}{2} e^Y, \quad \omega_2 = \frac{W_{\gamma\gamma}}{2} e^{-Y}, \quad (3.9)$$

$$\frac{d\omega_1}{\omega_1} \frac{d\omega_2}{\omega_2} = \frac{2}{W_{\gamma\gamma}} dW_{\gamma\gamma} dY, \quad (3.10)$$

$$d\omega_1 d\omega_2 \rightarrow dW_{\gamma\gamma} dY \text{ where } \left| \frac{\partial(\omega_1, \omega_2)}{\partial(W_{\gamma\gamma}, Y)} \right| = \frac{W_{\gamma\gamma}}{2}, \quad (3.11)$$

formula (3.7) can be rewritten as:

$$\begin{aligned} \sigma(AA \rightarrow AAD\bar{D}; s_{AA}) &= \int \hat{\sigma}(\gamma\gamma \rightarrow D\bar{D}; W_{\gamma\gamma}) \theta(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A) \\ &\times N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) \frac{2}{W_{\gamma\gamma}} d^2\mathbf{b}_1 d^2\mathbf{b}_2 dW_{\gamma\gamma} dY. \end{aligned} \quad (3.12)$$

Finally, the nuclear cross section can be expressed as the five-fold integral:

$$\begin{aligned} \sigma(AA \rightarrow AAD\bar{D}; s_{AA}) &= \int \hat{\sigma}(\gamma\gamma \rightarrow D\bar{D}; W_{\gamma\gamma}) \theta(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A) \\ &\times N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) 2\pi b_m db_m d\bar{b}_x d\bar{b}_y \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY, \end{aligned} \quad (3.13)$$

TABLE I: Total cross section for the exclusive $D\bar{D}$ production for RHIC ($s_{NN}^{1/2} = 200$ GeV) and LHC ($s_{NN}^{1/2} = 5500$ GeV) calculated with distribution amplitudes from [5] and [10].

Process	σ_{tot}	
	BCS94 DA	ZH2007 DA
$AuAu \rightarrow AuAu D^+ D^-$	12.44 nb	0.08 μb
$AuAu \rightarrow AuAu D^0 \bar{D}^0$	21.2 nb	5.06 nb
$PbPb \rightarrow PbPb D^+ D^-$	1.68 μb	1.92 μb
$PbPb \rightarrow PbPb D^0 \bar{D}^0$	4.09 μb	0.28 μb

where $\bar{b}_x \equiv (b_{1x} + b_{2x})/2$, $\bar{b}_y \equiv (b_{1y} + b_{2y})/2$ and $\vec{b}_m = \vec{b}_1 - \vec{b}_2$ have been introduced. This formula is used to calculate the total cross section for the $AA \rightarrow AAD\bar{D}$ reaction as well as the distributions in the impact parameter $b = b_m$, the meson invariant mass $W_{\gamma\gamma} = M_{D\bar{D}}$ and the meson pair rapidity $Y(D\bar{D})$.

IV. RESULTS FOR THE NUCLEAR COLLISIONS

In this section we present results for gold-gold collisions at RHIC ($W_{NN} = 200$ GeV) and lead-lead collisions at LHC ($W_{NN} = 5.5$ TeV). In all the calculations presented here we use realistic charge form factor being a Fourier transform of the realistic charge densities. Both $D^+ D^-$ and $D^0 \bar{D}^0$ channels are discussed. Below we present quantities which can be easily calculated in the b-space EPA discussed in the previous section. In Table I we have collected numerical values of the cross sections for considered exclusive processes. The cross sections are small but the reactions seem measurable especially at LHC.

Before we go to the presentation of more interesting quantities we wish to show a control plot. In Fig.5 we show distributions in the auxiliary variables b_x and b_y defined in Section III. These distributions are peaked at $b_x, b_y = 0$ and strongly decrease with increasing $|b_x|$ or $|b_y|$. This figure demonstrates that the chosen range of integration over the auxiliary variables b_x and b_y is sufficient. Please note that the range of integration for the LHC energy is 5 times larger than that for the RHIC energy. To speed up calculation we have performed integration in only two quadrants in the (b_x, b_y) space and used relevant symmetry relations.

In the heavy-ion photon-photon processes particles can be produced when nuclei fly far away apart. This is particularly spectacular for light leptons (see e.g.[2]). In Fig.6 we show such a distribution for the pseudoscalar $D\bar{D}$ production. The maximum of the cross section is for the impact parameter b when colliding nuclei almost touch each other and the cross section decrease for larger b . The decrease is much sharper for RHIC than for LHC. Compared to light leptons [2] here it is easier to achieve a convergence in b .

Now we come to the distributions which can be directly measured in experiments. In Fig.7 we show the distribution in the $D^+ D^-$ and $D^0 \bar{D}^0$ pair rapidity being $Y \approx \frac{1}{2}(y_D + y_{\bar{D}})$. The visible irregularities at larger $|Y|$ are caused by the oscillating nuclear form factor. The larger meson pair rapidity the larger four-momentum squared of the exchanged photon (which is the argument of the charge form factor). The irregularities correspond to the four-momentum squared when the charge form factor changes its sign, i.e. when $|F|^2$ is close to zero. A more elaborate discussion on the role of the nuclear form factor can be found in Ref.[2].

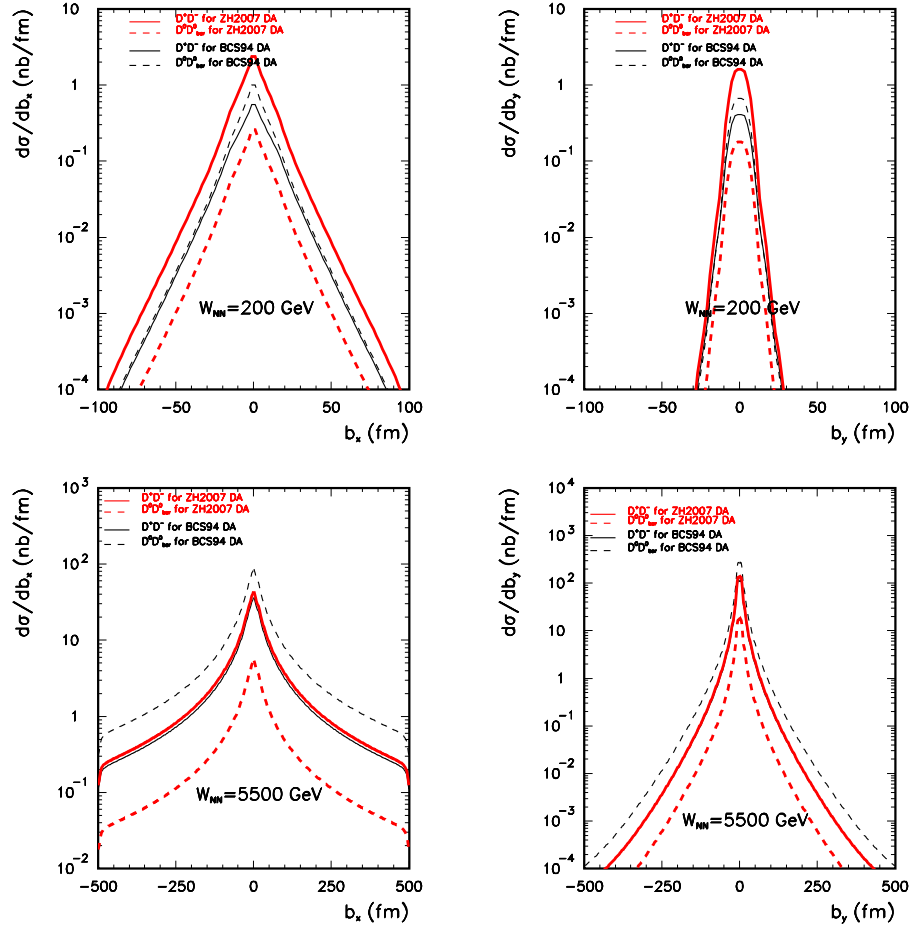


FIG. 5: The distributions in the auxiliary quantities b_x and b_y defined in section III for D^+D^- and $D^0\bar{D}^0$ for the BCS94 DA [5] (black) and for the ZH2007 DA [10] (red) for RHIC and LHC energies.

In Fig.8 we show distribution in invariant mass of D and \bar{D} . We predict steep fall-off of the distribution as a function of the invariant mass, even steeper than for the elementary cross section shown in Fig.3. This figure shows that in experiments only a region of small invariant masses close to the threshold could be investigated.

V. CONCLUSIONS

We have calculated for the first time in the literature total and differential cross sections for exclusive production of pseudoscalar $D\bar{D}$ meson pairs in the $AA \rightarrow AAD\bar{D}$ reaction assuming that the reaction is driven by the $\gamma\gamma \rightarrow D\bar{D}$ subprocess. The elementary cross sections were calculated in the heavy - quark approach as well as in the Brodsky- Lepage formalism with distribution amplitude describing recent CLEO data on leptonic D^+ decay. Rather small cross sections have been found. The cross section for exclusive $D\bar{D}$ production is much smaller than the cross section for the exclusive or semi-exclusive production of $c\bar{c}$ calculated recently. In our calculations absorption effects were included in the impact

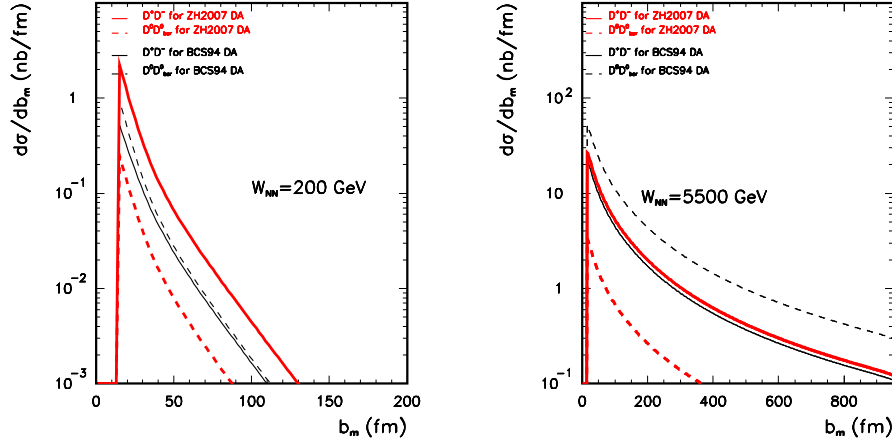


FIG. 6: Distribution in impact parameter for D^+D^- and $D^0\bar{D}^0$ for the BCS94 DA [5] (black) and for the ZH2007 DA [10] (red) for RHIC and LHC energies.

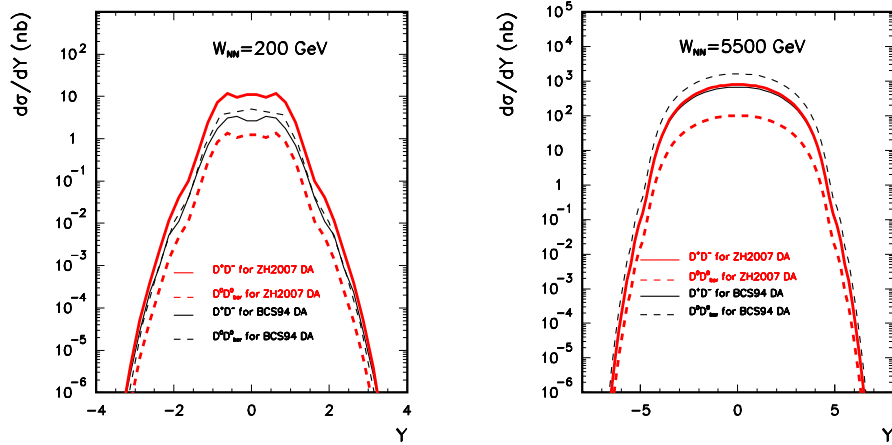


FIG. 7: The cross section as a function of the meson pair rapidity for D^+D^- and $D^0\bar{D}^0$ for the BCS94 DA [5] (black) and for the ZH2007 DA [10] (red) for RHIC and LHC energies.

parameter Equivalent Photon Approximation. The meson pairs are produced preferentially when the nuclei almost touch each other. The cross section strongly depends on the approximation made in the calculation. The dominant contribution to the cross section comes from the region of very small $D\bar{D}$ invariant masses.

Whether the process can be measured requires further dedicated studies including detector simulations. We believe that our evaluation will be a useful starting point for such future studies. Since the cross section strongly depends on theoretical details experimental verification would be very helpful.

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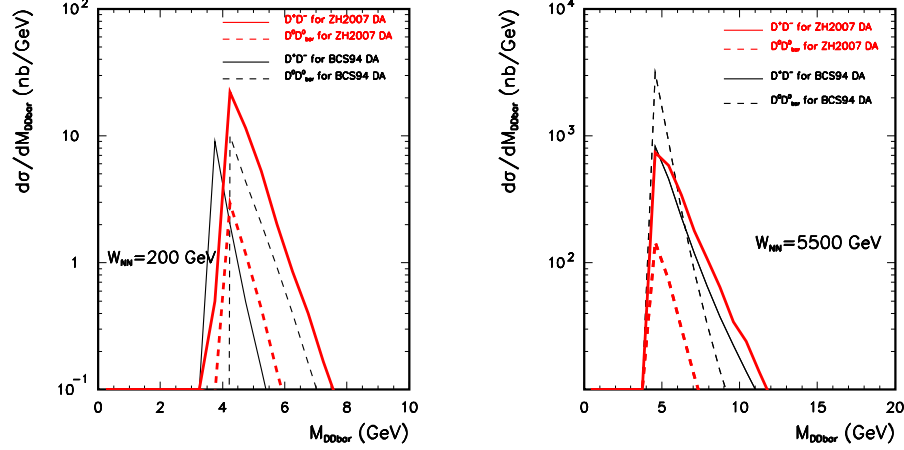


FIG. 8: $D\bar{D}$ invariant mass distribution for RHIC and LHC.

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